SEISMO-ACOUSTIC REMOTE SENSING OF THE ARCTIC ENVIRONMENT

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LONG-TERM GOAL(S)

Transitioning of acoustic ASW technology into environmental remote sensing techniques for characterizing ice-mechanical, oceanographic, and geophysical processes, climate change, and marine mammal behavior in the Arctic.

SCIENTIFIC/TECHNICAL OBJECTIVES

Fundamental understanding and modeling of the generation, propagation, and scattering of sound in and below the ice cover. The specific objective of the MIT/WHOI effort under SIMI has been to use seismo-acoustic remote sensing and subsequent inversion for characterization of ice fracturing processes and their relation to the environmental forcing.

The CEAREX and SIMI field experiments have also provided a comprehensive database of experimental data important to the other environmental remote sensing potentials. Thus, a significant part of our SIMI effort has been devoted to the modeling and analysis of the recordings of the 1994 Transarctic Acoustic Transmissions (TAP). In addition we are collaborating with marine biologists on the analysis of marine mammal sounds in our database.

APPROACH

The seismic fracture event data from SIMI-94 were obtained through real-time array processing and adaptive deployment. The hydrophone array was used to locate ice events by real-time processing. Mobile geophone arrays were then deployed in active

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zones to collect high-resolution seismic near-field data allowing for 'first-motion' fracture plane analysis.

The fracture event analysis is performed using a combination of acoustic and seismic data processing. The acoustic estimation of ice fault motion is performed in three steps:

1. particle motion (slip, particle velocity rise time): estimated through the analysis of the event signals in the time domain.
2. propagation (source speed, strike angle and source dimensions): estimated through the analysis of event signals in the frequency-domain, including Doppler-shift estimation from the event spectra and estimation of source dimensions from the source-wave displacement spectra.
3. type of ice mechanism: estimated through the analysis of the event radiation characteristics. Four even sub-populations have been identified, according to the acoustic model which best describes the event radiation pattern: a) events attributed to floe unloading, radiation from which is represented by a stationary dipole, b) events attributed to tensile fracture, radiation from which is represented by a weighted superposition of longitudinal octopoles, c) events attributed to shear fracture, modeled by a lateral octopole, and d) events attributed to shear fractures propagating in the medium through the formation of secondary arrays tensile cracks.
4. radiation from such a fracture phenomenon has been modeled by a hybrid multipole, consisting of a weighted superposition of a lateral octopole (to account for shear in one plane) and a combination of longitudinal octopoles (to account for tension in the perpendicular plane). (Figure 3) The analysis of large-scale acoustic activity is performed by analysis of events in the aggregate, i.e., temporal and spatial clusters. In particular, particle velocity, fracture speed, seismic moment and stress drop are examined for each cluster. (Figure 4).

One of the seismic processing approaches employed for analysis of the near-field data from the geophone clusters is based on the motion-product seismograms (MPS) introduced by J.E. White [4]. In this method each of the horizontal components of ice motion is multiplied by the vertical component, with or without phase shift, and after integration the two resulting products identified a vector pointing to the source of the seismic waves, Figures 1 and 2.

In relation to TAP, the MIT effort has focused on array processing and development of improved numerical models of long range propagation, with particular emphasis on consistent, coupled treatment of rough ice scattering and the ocean waveguide propagation [1,2,3]

One of the obstacles to using acoustic thermometry of the oceans is the potential effect on marine mammals. In collaboration with marine biologists at WHOI, the SIMI-94 data, and data from previous ice camps are being scanned for marine mammals, and high-resolution array processing is being used for tracking.

TASKS COMPLETED OR TECHNICAL ACCOMPLISHMENTS

One Ph.D. thesis (Stamoulis) has been completed in 1997 on acoustic inversion of a large number of fracture events in the area around the SIMI-94 arrays. The achievements of this thesis are summarized as follows:

1. Particle motion of fault processes in the ice has been consistently estimated for a large event population. Particle slip in the ice is:
   $O10^{-4}$ - $O10^{-2}$ m and particle velocity is in the range < 1 - 67 cm/s
2. Propagation and in particular source speed and dimensions have been estimated. Propagation speed is predominantly in the range 200-1100 m/s, significantly lower than the previously assumed Rayleigh wave speed. There is a wide range of speed estimates indicating the multitude of event-generating mechanisms and/or the occurrence of the latter at different stages in the their formation
3. Based on the analyzed event radiation characteristics, the proposed ice mechanisms, in the frequency range of analysis (10-350 Hz) are:
   - Unloading motion, which occurs both in the low- and mid-frequency ranges, i.e., both below and above 100 Hz
   - Shear fracture, which occurs in the mid-frequency range
   - Tensile fracture, which also predominantly occurs in the mid-frequency range
4. Secondary fracture details, such as arrays of tensile cracks formed at the tips and edges of shear fractures to enable them to propagate for large distances, affect the radiation due to shear motion. A hybrid acoustic model is then necessary to adequately describe radiation from such process.
5. Large-scale ice motion characteristics have also been estimated. In particular, the occurrence of process zones, consisting of a large number of small cracks, and the coalescence of echelon arrays of tensile cracks in the vicinity of shear fractures have been identified as plausible ice mechanisms.

Another Ph.D. thesis is expected to be completed in 1998 on the analysis of seismic events recorded by the RLAM geophone clusters deployed in active zones during SIMI-94.

One of the areas most rich in ice events was located on a small ice floe (100x100 m) 4 km North-East of the main camp, where the seismic array consisting of five 3-component geophones in an 70 m aperture pentagon was deployed.

A specific accomplishment in 1997 is the use of motion-product seismograms (MPS) to separate different polarizations of the seismic waves and to determine the direction to the source. Among the many processing approaches applied to this data, MPS was especially useful for geophone array data, because other analysis methods for such data occasionally failed due to the overlapping of waves generated by different ice events. Using the polarization processing method the development of ice fractures in the array near-field was successfully tracked in the time and spatial domains Figs.1 and 2. One result of the polarization analysis was that these fractures seemed to mostly generate vertically polarized shear (SV) waves, Fig. 1.

An MS thesis was completed in 1997 (Paeng) on an extension of the normal-mode scattering model by Tracey to handle layered elastic bottoms.

RESULTS

The modeling and analysis of the TAP experiment has lead to a dramatic improvement in the understanding of the role of ice interaction in long-range acoustic propagation, in particular the role of scattering into flexural waves as the dominant loss mechanism. This, in combination with the surface duct yields significant 'mode stripping', which all but eliminates the lowest order modes for Transarctic propagation.

IMPACT(S) FOR SCIENCE & TECHNOLOGY AND/OR APPLICATION

The improved Arctic propagation loss models developed under this program are currently being applied for performance predictions for the Arctic Acoustic Tomography Project (AATP).

The improved understanding of the acoustic emission from ice fractures can lead to better future ambient noise prediction models.

The matched field processing concepts developed under this program form the basis for acoustic tomography and AUV navigation methods applied in relation to the development of Autonomous Oceanographic Sampling Networks (AOSN).

TRANSITIONS ACCOMPLISHED AND EXPECTED

The 3-D elastic ice scattering theory developed at MIT is being applied to ONR sponsored research by BBN and Alliant Techsystems. The Arctic model losses predicted by the model are being used in normal-mode codes for the AATP modeling performed by SAIC and MIT.

The scattering formulation has been combined with the OASES code to provide a unique modeling capability for 3-D, bistatic reverberation from patches of anisotropic bottom or ice roughness [5]. This model is currently being transitioned to research in multi-static seabed acoustics at MIT, sponsored by ONR (Code 321OA).

The OASES model continues to be upgraded and made available to the community. Several universities and laboratories in the US, the Far East and Europe have received the newest OASES Version 2.1 via our Web-site:

<http://dipole.mit.edu:8001/arctic0/henrik/www/oases.html> .

RELATIONSHIP(S) TO OTHER PROJECTS FOR ONR OR OTHER AGENCIES

The acoustic and seismic scattering and reverberation work has strong relationship to ONR funded work at MIT in structural acoustics. The 3-D scattering work is co-sponsored by code 321OA.

The matched field processing concepts originally developed under this project are currently being applied in relation to AOSN research and development, Code 322 OM, and for adaptive signal processing
research under Code 321 SP.

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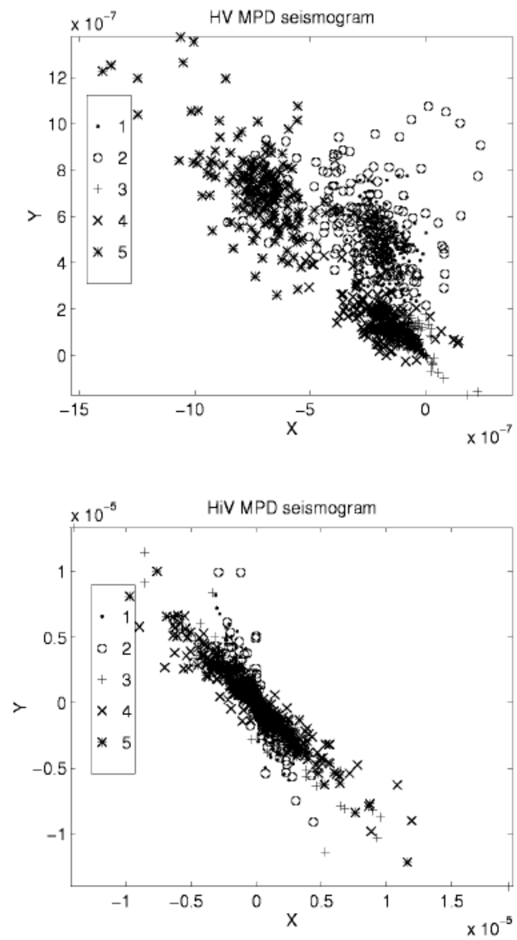

Figure 1: Comparison of outputs of HV (without phase shift) and HiV (with phase shift of $\pi/2$ between horizontal and vertical components) motion product seismograms for first event of the file #5 (tape 26). Top plot corresponds to HV seismogram, bottom one - to HiV seismogram. Different markers correspond to results for different geophones (identified by numbers from 1 to 5). This comparison shows that vertically polarized shear (SV) waves are dominant in this event.

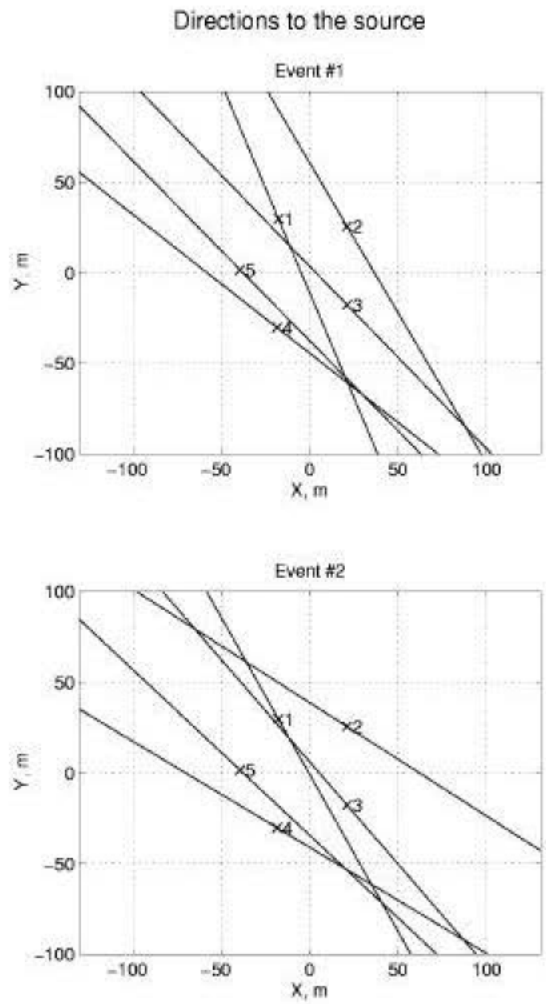

Figure 2: Directions to the source as given by outputs of HiV (with phase shift of $\pi/2$ between horizontal and vertical components) motion product seismograms for two events. Top plot corresponds to the first event of the file #5 (tape 26), bottom one - to the second event from the same file. On both plots locations of geophones (identified by numbers from 1 to 5) are shown by crosses. The comparison of the plots shows that using results for geophones #1, 4 and 5 events could be reliably located. The geophones #2 and 3 give quite different results, probably, due to drastically different local conditions of ice.

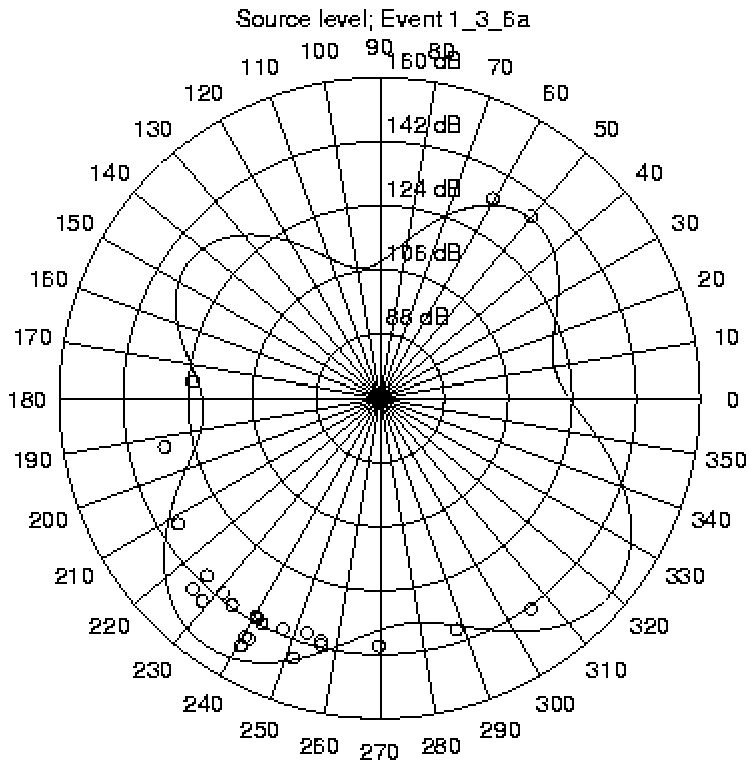

Figure 3: Horizontal radiation pattern of acoustic event, induced by a shear fracture that propagates in the medium through the formation of a tensile cracks at its tips and edges. Source level (in dB re 1 mPa, 1 Hz and 1 m) as a function of azimuth is plotted, and the acoustic radiation pattern is superimposed. The latter assumes that shear occurs along the *y* - *z* plane and tension along the *x*-axis. It is composed of a combination of a lateral octopole (to account for shear fracture) and a weighted superposition of longitudinal octopoles (to account to tensile fracture).

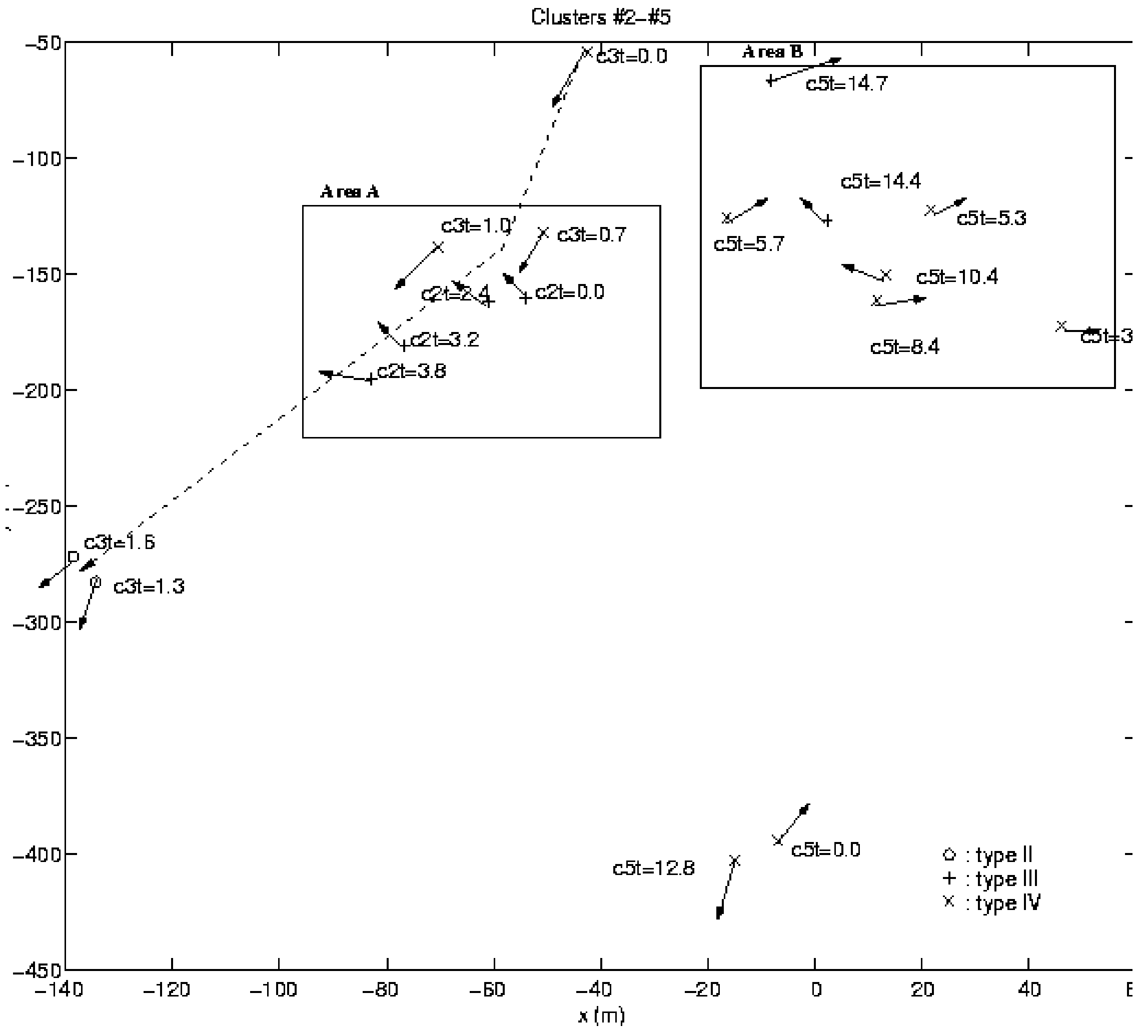

Figure 4: Event locations for clusters 2-5. Arrows indicate the estimated source orientations. The dashed line represents a possible path of fracture propagation. There are two areas, A and B, in which events cluster. In area A, the events are attributed to tensile fracture and their orientation is almost perpendicular to the traced uni-directional path, indicating the possible occurrence of echelon arrays of tensile cracks. In area B, the events' low mean source speed (~ 340 m/s) and low seismic moment ($O(10^7)$ Nm), as well as their random orientation suggest that these events may have been generated by secondary cracks, and thus area B may correspond to a process zone.